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Development of the load-deformation curve for bridge piers subjected to ship impact
Développement de la courbe charge-déformation pour des piles du pont exposés à la collision du navire.

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Keywords: Bridge, ship impact, load-deformation, piers, pile groups

ABSTRACT: On behalf of the Danish Ministry of Traffic a number of existing bridges in Denmark, have been examined against ship impacts. Several bridge piers were supported by pile groups, and part of the analysis was to determine the load-deformation curve for the piers, adjusting for pile group effect, partly mobilized earth pressure, the withhold of the bridge and applying plasticity theory. The establishment of the load-deformation curve at two different locations, respectively wood and concrete piles, using a PC-version of a non-linear structural program, is presented in this paper.

RESUME: Au nom du Ministère des Transports un nombre de ponts existants au Danemark ont étés examinés considérant des collisions du navire. Plusieurs des piles du pont étaient appuyés par des groupes de piles, et une partie de l'analyse était exécutée pour déterminer la courbe charge-déformation pour les piles, adaptée à l'effet de la groupe de piles, pression des terres partiellement mobilisée, la raideur du pont et la théorie de plasticité en vigueur. L'établissement de la courbe charge-déformation sur deux localités differentes, des piles en bois et en béton, respectivement, utilisant une version PC d'un programme structurel non linéaire, est présenté dans le present papier.

1 BASIS FOR INVESTIGATIONS

Prior to 1964 bridges in Denmark were not required by the Danish Codes to be examined in the design to withstand ship impact. In 1996 the Danish Ministry of Traffic started an investigation round, examining existing bridges in Denmark, towards their capacity in case of ship impacts or different iceloads. Several bridges were supported or partly supported by pile groups.

Two bridges in the southern part of Denmark, Svendborg Sound Bridge and the Langeland Bridge, see Figure 1, were picked for a more detailed analysis.

1.1 *The Langeland Bridge, across the Rudkøbing Channel*

The work on the Langeland Bridge was initiated in spring 1960 and the bridge was open for traffic in November 1962. The bridge is an arched concrete bridge, 774 m long, with abutments on both sides 425 m and 560 m long respectively. Due to findings of plastic clay, a number of the bridge piers were placed on piles.

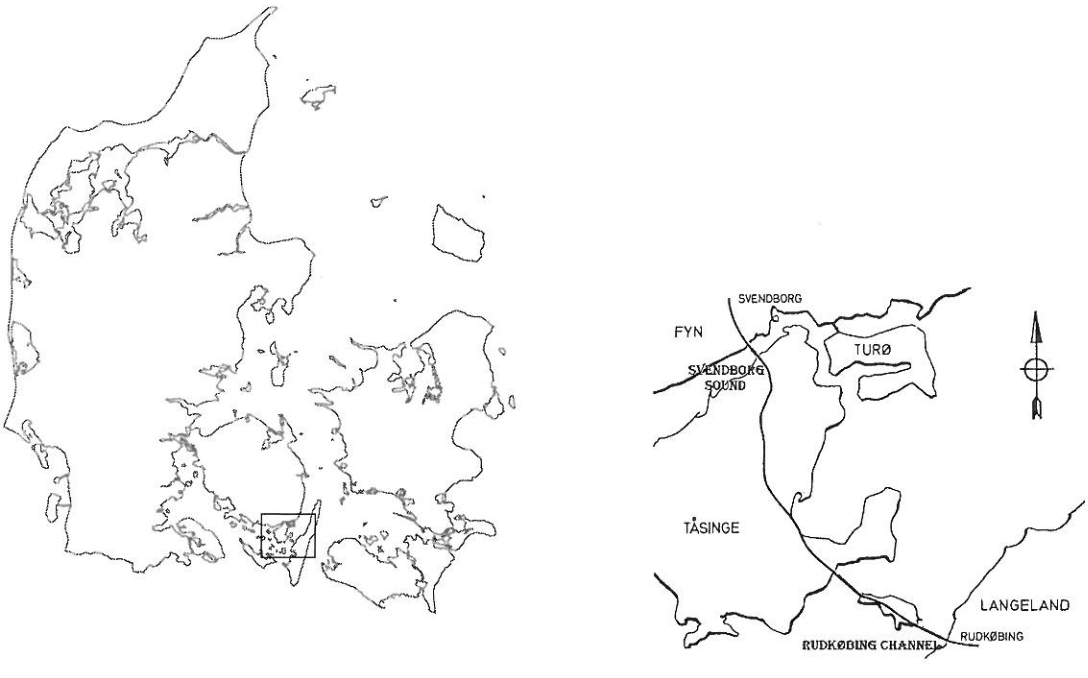

Figure 1. Location of the Svendborg Sound and Rudkøbing Channel

1.2 *The Svenborg Sound Bridge*

Svendborg Sound Bridge is a 1220 m long concrete suspension bridge, with girders resting on slender piers, to obtain an elegant structure that would dictate the landscape as little as possible.
The geological profile and the bridge being several times statically undetermined, lead to a foundation of the bridge, where one side of the bridge is directly founded on the clay till, the other side placed on piled foundations from this point forward, only the piled solution will be dealt with.

2 SOIL PROFILES

For each of the bridges, the original geotechnical investigations were revisited, and a design profile for the most critical piers was created, the profiles are shown in Figures 2 and 3.
The design soil profile with characteristic soil parameters forms the basis for all analyses: ULS, SLS and ALS. The ship impact analysis would range as an ALS (Accidental Limit State), where the settlement analysis would be characterized as SLS (Serviceability Limit State).

depth (m): 1.0, 2.4, 4.1, 7.0, 20.0, 35.0 (scale changed)

DESIGN PARAMETERS								
Soil type	γ' (kN/m³)	φ (deg)	c_u (kPa)	E (MPa)	ϵ_{50} (%)	t_c (kPa)	t_t (kPa)	q (MPa)
CLAY	2.00		50.0	20.0	0.8	20.0	20.0	0.4
CLAY	2.00		50.0	20.0	0.8	20.0	20.0	0.4
SAND	9.00	30.0		3.5		7.5	2.5	0.2
SAND	10.00	40.0		23.1		20.8	6.9	2.2
TILL	11.00		250.0	100.0	0.4	100.0	100.0	4.5
TILL	12.00		350.0	140.0	0.3	140.0	140.0	6.3

γ' : Submerged unit weight
φ : Angle of internal friction
c_u : Undrained shear strength
E : Modulus of elasticity
ϵ_{50} : Strain which occurs at one-half of the maximum stress in laboratory undrained compression test
t_c : Unit skin friction, compression
t_t : Unit skin friction, tension
q : Unit tip resistance, compression

SCOUR: Local scour: 0.0 m
Glocal scour: 0.0 m
Scour angle: 0.0 deg

Design code: DS415
Partial coefficient on angle of internal friction: 1.00
Partial coefficient on undrained shear strength: 1.00
Partial coefficient on axial bearing capacity: 1.00

Figure 2. Characteristic Design Soil Profile, Svendborg Sound Bridge

depth (m): 1.0, 2.5, 4.5, 7.0, 12.4, 13.0

DESIGN PARAMETERS								
Soil type	γ' (kN/m³)	φ (deg)	c_u (kPa)	E (MPa)	ϵ_{50} (%)	t_c (kPa)	t_t (kPa)	q (MPa)
CLAY	8.00		200.0	80.0	0.4	80.0	80.0	1.8
CLAY	8.00		200.0	80.0	0.4	80.0	80.0	1.8
CLAY	8.00		200.0	80.0	0.4	80.0	80.0	1.8
CLAY	8.00		200.0	80.0	0.4	80.0	80.0	1.8
CLAY	8.00		200.0	80.0	0.4	80.0	80.0	1.8
CLAY	8.00		100.0	40.0	0.6	40.0	40.0	0.9

γ' : Submerged unit weight
φ : Characteristic angle of internal friction
c_u : Characteristic undrained shear strength
E : Modulus of elasticity
ϵ_{50} : Strain which occurs at one-half of the maximum stress in laboratory undrained compression test
t_c : Unit skin friction, compression
t_t : Unit skin friction, tension
q : Unit tip resistance, compression

SCOUR: Local scour: 0.0 m
Glocal scour: 0.0 m
Scour angle: 0.0 deg

Design code: DS415
Partial coefficient on angle of internal friction: 1.00
Partial coefficient on undrained shear strength: 1.00
Partial coefficient on axial bearing capacity: 1.00

Figure 3. Characteristic Design Soil Profile, Langeland Bridge, across the Rudkøbing Channel

3 PILES

The timber piles used at the Langeland bridge, are Danish Pine with a mean diameter of 36 cm. In the model the piles are models as circular wooden piles with a diameter of 360 mm.

Square concrete piles are used at the Svendborg Sound Bridge, these are modelled as 0.4 x 0.4 m^2 prestressed concrete piles with a characteristic strength, f_{ck}, of 40 MPa.
A typical foundation and location of piles for each of the bridges are depicted in Figure 4.

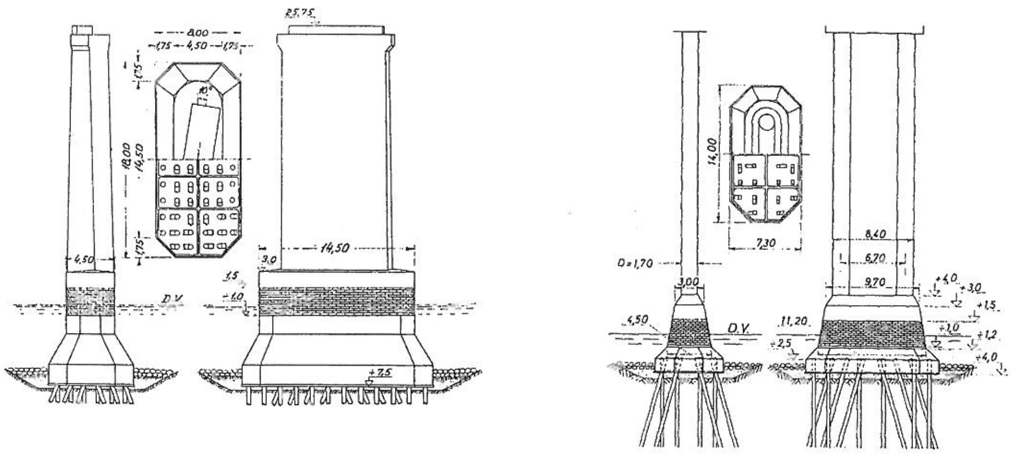

Figure 4. Typical foundation and pile location plan (a) Langeland Bridge (b) Svendborg Sound Bridge

4 MODEL

The calculations are performed using a PC version (PCPILE) of a non-linear structural program (ROSAP) developed by RAMBØLL. PCPILE differ from ROSAP in the way that it assumes the foundation slap to be infinite stiff.

4.1 *Soil curves*

The soil is modeled in ROSOIL, in terms of soil curves describing the axial (t-z curves) and lateral (p-y curves) interaction, combined with the end bearing deformation (q-w curves) as depicted in Figure 5. The curves are modeled according to API code and the Danish Code of Practice

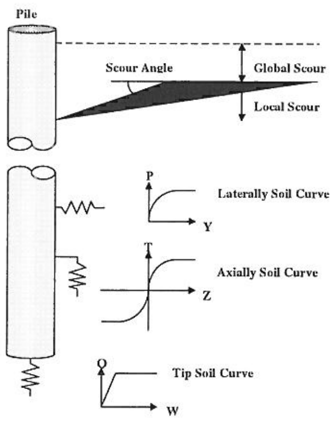

Figure 5. Illustration of soil curves used in ROSOIL

In the soil curves the undrained shear strength of the plastic clay (Lillebæltsleren) has been reduced for lateral load and end bearing to: $c_u = \frac{1}{3} \cdot c_v$; according to the Danish Code of practice.

4.2 *Loads and corrections influencing the model*

The interaction between the piles, corresponding to a distance of 6 times the pile diameter, was accounted for. When a fully activated passive earth pressure, corresponding to a deformation of 1% of the foundation wall height (at approx. 15 mm deformation), occurred the model was corrected for an earth pressure resultant acting on the front of the foundation.

The model was loaded for death weight of the bridge structure and a load acting at the point of the ship impact, dealing with directions, seabed locations etc. This ship impact was increased stepwise and a load-deformation curve was established. In Figure 6 the load-deformation curve is depicted for the ship impact at the Langeland Bridge.

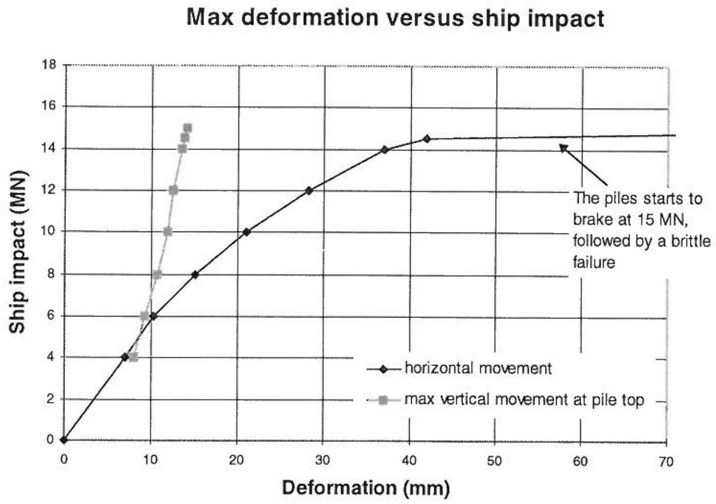

Figure 6. Vertical and horizontal deformation of the foundation illustrated as function of the ship impact at the Langeland Bridge, acting 6.5 m above the foundation level.

The model in PCPILE showed that the first wooden piles reached their maximum capacity at a ship impact of 15 MN, the piles were then removed and replaced with a resulting moment corresponding to the moment in the top of the pile caused by the ship impact.

The load was redistributed and if the foundation had additionally capacity the load was increased. For the wooden pile solution, the maximum capacity was reached instantaneously and a brittle failure occurred.

The bending moment and corresponding normal force in all piles are illustrated for a ship impact of 15 MN in Figure 7, corresponding to the time when the first 4 piles starts to yield, and when all the tension piles are removed

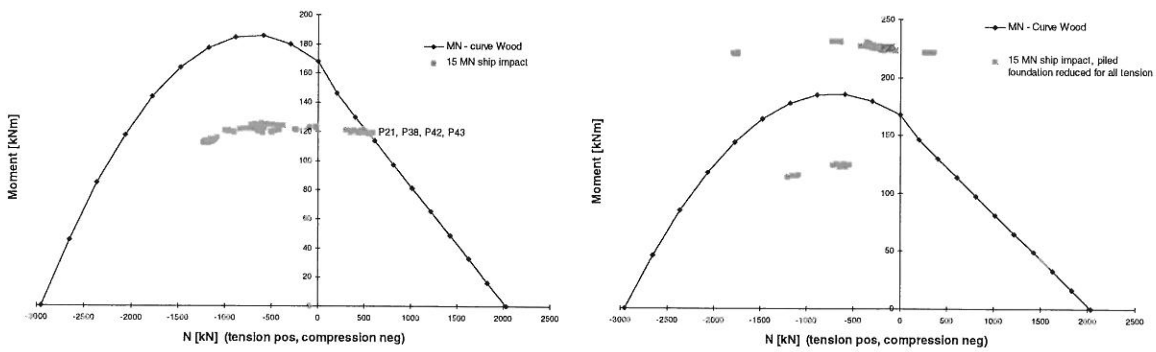

Figure 7. The bending moment and corresponding normal force for a ship impact of 15 MN. (a) in all piles, (b) when all tension piles are removed.

5 PLASTICITY THEORY

For the concrete piles at Svendborg Sound, the model was transferred to the ROSAP program when the first piles reached their first yield point. This Translation allowed for equipping the piles with a pivot at the yield point and a moment corresponding to the present bending moment.
All piles were left in the model, the load was increased and pivots applied until the on pile had 2 yield points. At this impact the foundation had reached the maximum capacity and the foundation would collapse.
The load-deformation curve for the horizontal movement of the piled foundation is shown in Figure 8 together with the bending moment-normal force diagram for the poorest loaded piles.

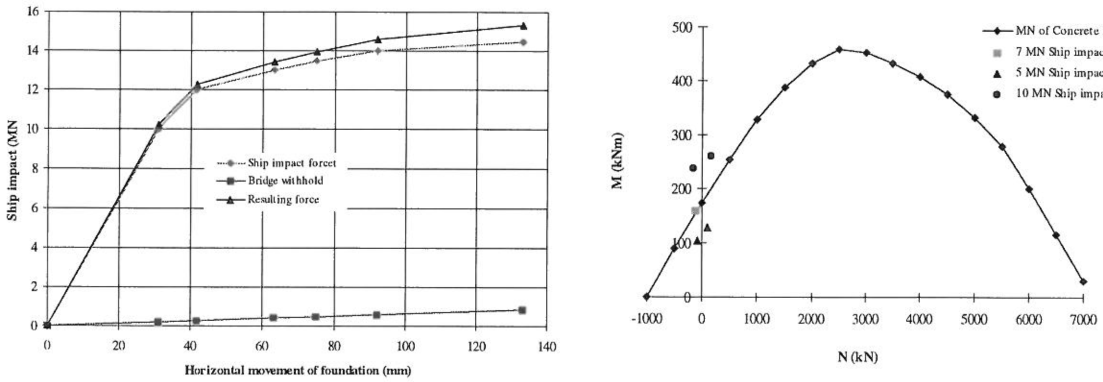

Figure 8. (a) Load-deformation curve for horizontal movement of the piled foundation. (b) bending moment-normal force curve for the poorest loaded piles at respectively 5, 7 and 10 MN ship impact

6 CONCLUSION

The load-deformation curve was established for both foundation types based on the given geometry, incorporating both pile group effect, withhold from earth pressure and bridge.
When a piled foundation is placed on prestressed concrete piles it has proven evident that applying plasticity theory on the steel enlarges the bearing capacity of the piles, thus the load deformation curves can be extended and as a result the bridge is enabled to absorb larger ship impacts.
The outcome of the investigation of the two bridges proved that the bridge across the Rudkøbing Channel could withstand a larger ship impact then the statistically determined design impact, where the analysis of the Svendborg Sound bridge resulted in the design and placement of two new protective caissons.

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